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Effect of installation angle of fins on melting characteristics of annular unit for latent heat thermal energy storage

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Abstract

Latent heat thermal energy storage (LHTES) technology can solve the problem of a mismatch between energy supply and demand in time, space and intensity and thus has become a research on focus in energy and environmental protection. The low thermal conductivity of phase change materials (PCMs) is the primary bottleneck of the popularization application of LHTES technology. An effective way to solve this problem is adding fins into the PCM container to enhance heat transfer, there has been no report on the effect of the installation location of fins on the heat transfer characteristics of the PCM in a LHTES unit. To study the effect of fins installed at different locations on the heat transfer, this work have investigated the melting characteristics of PCM in an annular with different installation angle of fins (θ) via a numerical simulation method, which is based on an enthalpy-porous medium model. In addition, the numerical calculation results are verified via experimentation. On this basis, the melting processes of the PCM in horizontal, annular units with fins installed at five different values of θ under three fixed wall temperature conditions (60, 70, and 80 °C) have been simulated. The simulation results have been compared to those of the unit without fins. The results show that although fins inhibit natural convection, the addition of fins can lead to an increase in the melting rate and a decrease in the melting time due to an increase in the total amount of heat exchanged. Considering the entire melting process, the melting rate of the PCM in the unit with fins installed at $\theta = 0°$ is maximum. When θ reaches 45°, the further increase of θ has no marked impact on the melting rate of the PCM in the unit. Based on the trend of the change of the mean Nusselt number with the Fourier number (Fo), the heat transfer of the melting process of the PCM is divided into four stages. Additionally, the dimensionless criterion relationship between the melting fraction (f) and $SteFoRa^{1/6}$ when $\theta = 0°$ is fitted as $f = 0.24X^3 - 1.13X^2 + 1.82X$, where $X = SteFoRa^{1/6}$.

Keywords: Latent heat thermal energy storage (LHTES) unit; Heat transfer enhancement; Installation angle of fins; Numerical simulation

1. Introduction

The world is currently facing a serious challenge with regard to energy shortages. In the energy structure, the amount of energy provided in the form of heat accounts for a considerable proportion of the total amount of energy provided. Therefore, efficient and environmentally friendly heat utilization technologies are of particular importance. Latent heat thermal energy storage (LHTES) technology, which is based on the physical mechanisms of phase change materials (PCMs), is an important technology that can improve heat utilization efficiencies (Liu et al., 2013). When a PCM undergoes a phase change, it absorbs or releases a large amount of heat, based on which LHTES systems store and release heat. Compared to other heat storage

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Nomenclature

A	total heat exchange area (m^2)
A_{mush}	mushy zone constant ($kg \cdot m^{-3} \cdot s^{-1}$)
c_p	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
D	characteristic size (m)
f	melting fraction
g	acceleration of gravity ($m \cdot s^{-2}$)
h	sensible enthalpy ($J \cdot kg^{-1}$)
h_f	height of fin (mm)
H	total enthalpy (J)
$\overline{K}$	mean heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
L	latent heat ($J \cdot kg^{-1}$)
P	pressure (Pa)
PCM	phase change material
Q	total amount of heat absorbed (W)
R_i	radius of inner annulus (m)
R_o	radius of outer annulus (m)
$\vec{S}$	damping term
T	temperature (°C)
t	time (s)
$\vec{V}$	velocity vector ($m \cdot s^{-1}$)

Greek symbols

α	thermal diffusivity ($m^2 \cdot s^{-1}$)
β	expansion coefficient (K^{-1})
ε	small number
θ	installation angle of the fins (°)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
μ	dynamic viscosity ($Pa \cdot s$)
v	kinematic viscosity ($m^2 \cdot s^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
δ	thickness of fin (mm)
ΔH	latent heat enthalpy ($J \cdot kg^{-1}$)
Δt	time interval (s)

Subscripts

m	melting
w	wall
l	liquid
s	solid
ref	reference

Nondimensional number

$Fo = \frac{\alpha t}{D^2}$	Fourier number
$\overline{Nu}$	Mean nusselt number
Ra	Rayleigh number
Ste	Stefan number

methods, the latent heat thermal energy storage method is advantageous because it has a high energy storage density; its system is simple and stable; and the heat storage/release process is an approximately isothermal process (Tay et al., 2015; Ye, 2015; Zhang et al., 2014a). LHTES method can thus effectively solve the mismatch between energy supply and demand in time, space and intensity and is widely used in engineering applications, such as solar energy utilization (Avci and Yazici, 2013; Al-Kayiem and Lin, 2014), building energy conservation (Barzin et al., 2015; Kuznik et al., 2008), industrial waste heat recovery (Nomura et al., 2010), heating and air conditioning (Mosaffa et al., 2012; Parameshwaran and Kalaiselvam, 2014), and electronic component cooling (Akhilesh et al.,2005). However, the main disadvantage of many PCMs, such as paraffin waxes and fatty acids, is the low thermal conductivity which has a severe impact on the performance of a LHTES system. The effect of low thermal conductivity is reflected in a long melting time and a marked temperature decrease during the energy retrieval process (Jegadheeswaran and Pohekar, 2009; Rathod and Banerjee, 2015). Therefore, it is necessary to improve the heat transfer performance of LHTES systems. To overcome the aforementioned shortcomings, researchers have proposed methods to enhance heat transfer by modifying the PCMs and units used. Methods that enhance heat transfer by modifying the PCM include adding the PCM to a porous of high thermal conductivity (Karaman et al., 2011; Yuan et al., 2014), adding powder with a high thermal conductivity(Zhang et al., 2014b), and micro/nano-encapsulating the PCM (Alkan et al., 2009; Fang et al., 2010; Wang et al., 2011). Methods for enhancing heat transfer by modifying the LHTES unit include increasing the heat transfer area (e.g., adding fins) (Li and Wu, 2015; Kamkari and Shokouhmand, 2014; Nayak et al., 2006; Rathod and Banerjee, 2015; Sharifi et al., 2011) and enhancing convection (e.g., producing an eccentric annular unit) (Dutta et al., 2008; Darzi et al., 2012; Dhaidan et al., 2013; Jourabian et al., 2014; Yazıcı et al., 2014).

Adding fins is a simple, easy, low-cost heat transfer enhancement method. The phase change rate of the PCM in an annular LHTES unit, which is commonly used in engineering and is thus reviewed and investigated in this study, can be increased by adding fins to the unit. Liu et al. (2005a,b) studied the melting and solidification characteristics of stearic acid in a vertical annular LHTES unit with axial fins and found that the addition of fins resulted in an increase in the melting and solidification rates of the stearic acid. Li and Wu (2015) investigated the effect of the addition of fins, the temperature of the heated fluid and the type of PCM on the heat transfer characteristics of a horizontal shell-and-tube LHTES unit. They found that both the melting and solidification times decreased by at least 14% after fins were added.